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Utilization of waste nitrogen for biofuel production in China

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ABSTRACT

Nitrogen (N) is the limiting factor for current biofuel production. Enormous quantities of waste N from agricultural, industrial and domestic use have been lost to the environment resulting in serious negative consequences. In this study, we discuss biofuel production using waste N (BPWN) on untilled or marginal land. Taking China as an example, the total waste N lost to surface water was estimated at 11.3 Tg N (1 Tg = 10^{12} g) in 2008, accounting for 40% of total fertilizer N applied to China's cropland. The total potential biofuel produced by waste N was estimated at 16,436.3 PJ $year^{-1}$ (1 PJ = 10^{15} J), accounting for ~20% of China's total energy consumption, or five times China's total gasoline demand in 2008.

The net energy balance (Output–Input) of BPWN is 570 GJ ha^{-1} $year^{-1}$ (1 GJ = 10^9 J) in China, about 15–30 times that of current major biofuel production systems (e.g. corn, switchgrass, low-input high-diversity grassland). The feasibility analysis shows that, although the land resources for BPWN are not sufficient in one-fifth of China's provinces if considering all of the potential waste N supply, the total maximum land requirement is only 17.5% of China's total untilled land resource. Further research on the imbalance between land requirement and waste N supply on the regional and local scales will help to refine the estimate of biofuel production potential.

Contents

1. Introduction

The energy crisis has given rise to concern over future energy supplies and global climate change, thus, sustainable alternative biofuels have attracted much attention [1]. The two current major biofuel production systems, monoculture crop and cellulosic ethanol biomass, are nitrogen (N) fertilizer dependent if a high-energy yield is expected [2,3]. However, the high N input of current biofuel production has led to a large amount of waste reactive N lost

Abbreviations: BPWN, biofuel production using waste nitrogen; CW, constructed wetland; DW, dry weight; GHG, greenhouse gas; LIHD, low-input high-diversity grassland; N, nitrogen; NEB, net energy balance; NER, net energy balance ratio; NUE, nitrogen use efficiency; WTP, wastewater treatment plant.

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Table 1
Productivity potential of aboveground biomass, N and land requirement and energy yield of current and potential biofuel plants.

Plant	Productivity ($MT ha^{-1} year^{-1}$)	Nitrogen requirement ($kg ha^{-1} year^{-1}$)	Net energy yield/N ($GJ kg^{-1}$ N)	Land requirement/N ($ha Gg^{-1}$ N)	Reference
Miscanthus[a]	25	200	2.1	5000	[21]
Giant reed[b]	45	600	1.2	1670	[20]
Napiergrass[c]	88	–	–	–	[24]
Alemangrass[d]	100	–	–	–	[24]
Corn	10	120	0.2	8333	[24]
Switchgrass[e]	11	75	1.0	13,333	[3]
LIHD[f]	6	–	–	–	[28]

1 MT = 10^6 g; 1 GJ = 10^9 J; 1 Gg = 10^9 g.
[a] Latin name of the plant is *Miscanthus* x *giganteus*.
[b] Latin name of the plant is *Arundo donax*.
[c] Latin name of the plant is *Pennisetum purpureum*.
[d] Latin name of the plant is *Echinochloa polystachya*.
[e] Latin name of the plant is *Panicum virgatum*.
[f] Latin name of the plant is including 18 perennial prairie species, e.g. *Lupinis perennis*, *Andropogon gerardi*, and *Poa pratensis*.

to the environment [3]. This, together with the waste N derived from agricultural, industrial and domestic use, has contributed to the massive waste N lost to the environment [4] and resulted in serious environmental problems, e.g. the 'dead zone' from the Gulf of Mexico [2]. Enormous investments have been spent to produce N fertilizers and solve the environmental pollution and human health problems driven by excessive waste N [5]. In this context, ideas for using the waste nutrients and biomass have been suggested which could supply biofuels without N fertilizer requirement [6].

The N loss from global cropland has been estimated at ~65 Tg N $year^{-1}$ (1 Tg = 10^{12} g) [7], and ~35 Tg N $year^{-1}$ from livestock production [8]. Meanwhile, human excretion has added ~20 Tg N $year^{-1}$ to the global environment [9]. These waste N levels lost to the environment supply an enormous potential for the nutrient requirement of biofuel production. Coupling the waste N and biofuel production can not only mitigate the global N pollution and reduce the investment in N pollution control [6], but can also provide N for biofuel production [10,11]. At the same time, there is a reduced health risk from using waste N for biofuel production compared to using it for agricultural food production [12]. This might be a win–win strategy for mitigating both the environmental N pollution and the energy crisis.

China, as the world's largest agricultural economy, consumes one-third of global fertilizer N production [13]. The over-fertilization on cropland [14] and the decoupling of livestock and cropland [15] in China have resulted in a large amount of waste N lost to the environment. The population of China ranks first globally, and the low domestic wastewater treatment ratio [16] has also contributed to the waste N discharge. The development of waste N patterns in China during the past few decades can be regarded as the epitome of the development history of developed countries, and can also offer a case study for the sustainable development of other developing countries. In this study, taking China as an example, we: (1) determined the potential for biofuel production using waste N (BPWN); (2) examined the spatial pattern of total and per capita BPWN potential; and (3) analyzed the feasibility of BPWN on the basis of water supply and land resources. The outcomes not only concern China, but might also provide a potential alternative route for solving environmental and energy problems in other countries.

2. Advantages of BPWN

Biofuel production using waste N by planting energy crops on untilled or marginal land is emphasized in this paper. Such an idea can be extended to biomass production using wastewater via constructed wetlands (CW) [17], cropland runoff via riparian buffer strip and marginal land [18], etc. Compared to current biofuel production, BPWN has the following advantages:

(1) There is no need for N fertilizer application and so it can reduce the cost of energy input and increase the net energy balance ratio (NER, Output/Input).
(2) BPWN can reduce environmental N pollution, the cost of pollution control and greenhouse gas (GHG) emissions since there is no need for the waste N to be treated via treatment facilities, e.g. wastewater treatment plant (WTP).
(3) Waste N is coupled to water supply, such as domestic wastewater, and the effluent water can be reused for irrigation; therefore, there is less water deficiency stress on BPWN.
(4) BPWN can use untilled or marginal land and so can avoid competing with food production on fertile soils.
(5) BPWN can also provide other ecosystem services, including renewal of soil fertility, and avoiding health risks since if the waste N is not being used for biofuel production, it might be used for agricultural food production instead.

3. Biomass and energy yield of BPWN

In this paper, BPWN was performed by planting two typical energy crops, *Arundo donax* and *Miscanthus* x *giganteus* [19–21]. *A. donax* is a native species in subtropical and tropical regions of China and has been used for biomass production in CWs [22]. *A. donax* has also been recommended as an energy crop in Australia and North America using wastewater irrigation [19,20]. The potential biomass production of *A. donax* can reach ~45 MT (1 MT = 10^6 g) dry weight (DW) ha^{-1} $year^{-1}$ with an N supply around 600 kg N ha^{-1} $year^{-1}$ [20]. *M.* x *giganteus* has been introduced to China as energy crop that is suitable for planting in the temperate zone and Qinghai–Tibet plateau [23]. As a novel energy crop in Europe, *M.* x *giganteus* can still achieve a high-energy yield in high latitude regions [19,21]. The biomass production potential of *M.* x *giganteus* can reach ~25 MT dry DW ha^{-1} $year^{-1}$ with a N supply around 200 kg N ha^{-1} $year^{-1}$ (Table 1). The average biomass production of BPWN with the above two species is much higher than that of switchgrass and low-input high-diversity (LIHD) grassland, as well as corn with considering the whole aboveground biomass (Table 1); however, it is still lower than that of the biofuel feedstock found in tropical regions, ~100 MT DW ha^{-1} $year^{-1}$ [24].

Compared to corn, switchgrass and LIHD grassland, the net energy balance (NEB, Output–Input) of BPWN is the largest, reaching 570 GJ ha^{-1} $year^{-1}$, followed by switchgrass, which is about one-tenth of that of BPWN, while the LIHD and monoculture crop biofuels are the smallest, at around 3% of that of BPWN (Fig. 1). The NER of BPWN is about 2–20 times that of corn, switchgrass and LIHD grassland (Fig. 1), since the no N fertilizer application (replaced by waste N) can largely reduce the energy input.

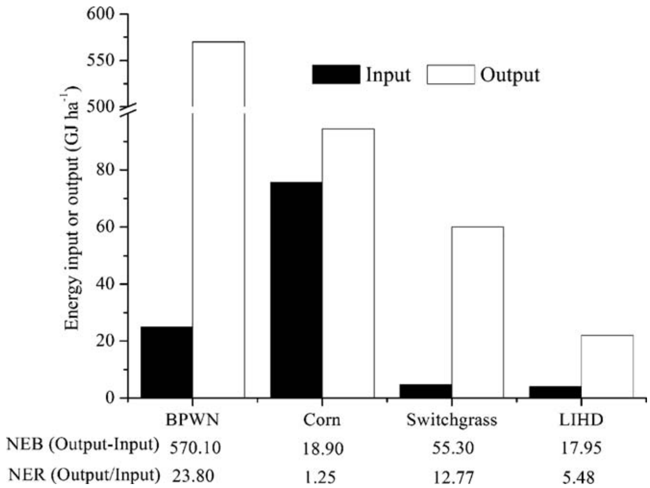

Fig. 1. NEB for biofuel production using waste N (BPWN), corn, switchgrass and low-input high-diversity (LIHD) grassland. NEB is the sum of all energy outputs (including co-products) minus the sum of fossil energy inputs. NER is the sum of energy outputs divided by the sum of energy inputs. Data for BPWN were from Refs. [19–21]; for corn, low-input high-diversity (LIHD) grassland and switchgrass, data were from Ref. [28].

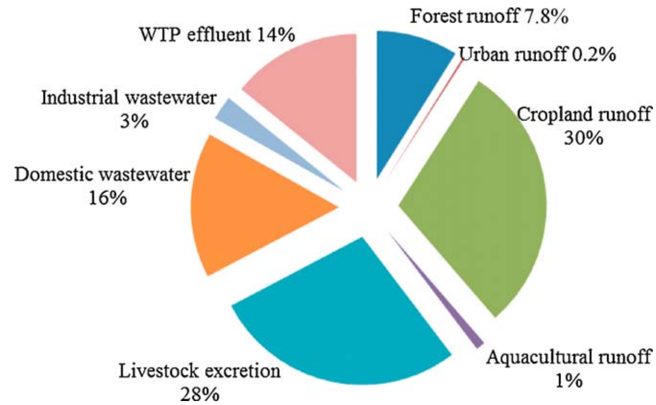

Fig. 2. Sources and their contribution to total waste N supply in China in 2008.

4. Estimation of the potential of BPWN in China

4.1. Waste N and potential energy production

In 2008, total waste N discharged to surface water in China was estimated at 11.3 Tg N, ~60% of which was non-point source pollution from agriculture, another ~30% was point source pollution from domestic and industrial wastewater and the rest, less than 10%, was mainly from natural ecosystem N flux, such as forests (Fig. 2). The total waste N production is 40% of total fertilizer N applied to China's cropland, or about 4.6 times Brazil's N fertilizer usage. In fact, half of the total N excretion from humans and livestock, ~18 Tg N year^{-1}, was recycled for agricultural production. Given that the N input for China's agriculture is overloaded [14], if the fertilizer and excretion N consumption in agriculture were balanced, then there might be more waste N that could be used for biofuel production (see Supplementary Data for estimation details).

On the basis of the above analysis, we examined three waste N supply scenarios (S1–S3) to estimate the biofuel production potential via BPWN in China (Table 2). Under S1 (current waste N supply),

Table 2
Potential biofuel production, and energy consumption in China in 2008 (100 PJ year^{-1}).

Province	S1	S2	S3	Energy consumption		S3/total (%)
				Total	Domestic	
Beijing	1.2	1.6	0.9	15.2	1.8	6.1
Tianjin	1.3	1.6	0.3	12.9	1.5	2.3
Hebei	13.4	15.8	15.8	58.5	6.7	26.9
Shanxi	4.8	5.8	5.8	37.7	4.3	15.3
Inner Mongolia	5.9	6.7	6.7	33.9	3.9	19.8
Liaoning	7.3	8.8	6.3	42.8	4.9	14.8
Jilin	7.8	8.9	4.7	17.4	2.0	27.3
Heilongjiang	8.7	10.1	10.1	24.0	2.8	42.1
Shanghai	0.6	0.7	0.7	24.6	2.8	3.0
Jiangsu	5.3	6.3	1.1	53.5	6.2	2.0
Zhejiang	3.2	3.9	3.9	36.3	4.2	10.8
Anhui	6.3	7.5	5.4	20.0	2.3	26.9
Fujian	2.9	3.6	3.6	19.9	2.3	18.0
Jiangxi	3.8	4.7	4.7	12.9	1.5	36.0
Shandong	17.9	20.9	6.9	73.5	8.5	9.4
Henan	21.6	25.1	7.9	45.6	5.3	17.2
Hubei	6.1	7.2	7.2	30.9	3.6	23.5
Hunan	7.1	8.5	8.5	29.7	3.4	28.6
Guangdong	6.6	8.2	7.0	56.5	6.5	12.3
Guangxi	5.6	6.7	6.7	15.6	1.8	42.6
Hainan	1.1	1.2	1.2	2.7	0.3	44.7
Chongqing	3.0	3.7	3.7	15.6	1.8	23.6
Sichuan	8.6	10.4	10.4	36.4	4.2	28.6
Guizhou	5.3	6.2	6.2	17.0	2.0	36.6
Yunnan	5.9	6.7	6.7	18.1	2.1	37.0
Tibet	3.8	4.0	4.0	2.8	0.3	140.2
Shanxi	6.6	8.0	4.9	17.8	2.1	27.5
Gansu	4.2	5.2	5.2	12.9	1.5	40.1
Qinghai	1.8	2.1	2.1	5.5	0.6	37.6
Ningxia	1.1	1.3	1.3	7.8	0.9	16.3
Xinjiang	4.1	4.6	4.6	17.0	2.0	27.1
China	182.9	216.0	164.4	812.4	93.6	20.2

S1–S3 indicate the waste N supply scenarios. S1: current waste N supply; S2: current waste N supply adding waste N treated via WTP to BPWN; S3: total waste N supply based on S2, and considering the feasible untilled land resources.

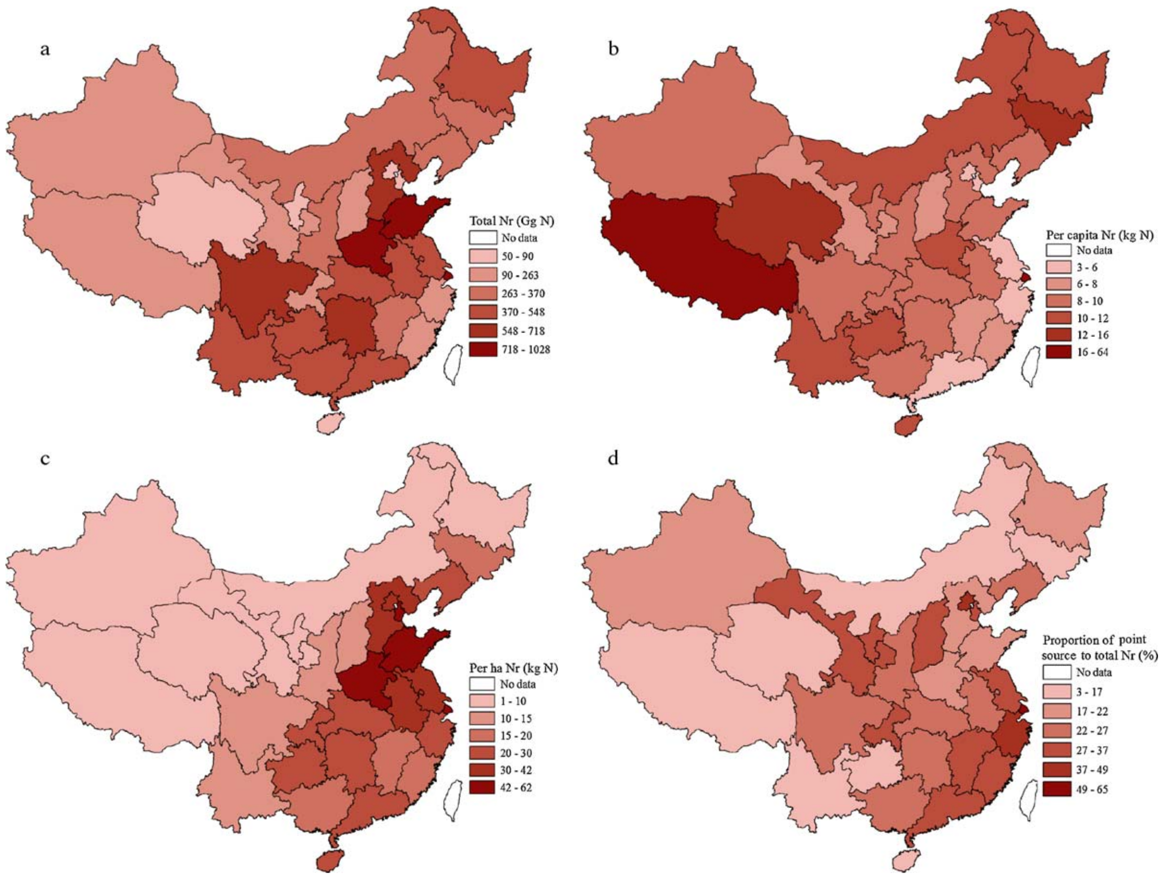

Fig. 3. Waste N distribution patterns in China in 2008; (a) total waste N; (b) per capita waste N; (c) per ha waste N; (d) proportion of point source waste N to total waste N.

China can produce 18,291.4 PJ year^{-1} biofuel. Under S2 (adding waste N that is treated via WTP to BPWN), the potential biofuel production via BPWN would increase 18%, to 21,595.9 PJ year^{-1}. However, for S1 and S2, the feasible land resource (untilled or marginal land) is not considered. Under S3, we calculated the feasible land supply for each province in China to test whether there are sufficient land resources for BPWN. If the feasible land resources were smaller than the land requirement by S2, then the potential biofuel production was re-calculated based on the feasible land resources. On the basis of the above analysis, we revised the potential biofuel production from 21,595.9 PJ year^{-1} under S2 to 16,436.3 PJ year^{-1} under S3 (Table 2). The potential biofuel production under S3 accounts for ~20% of China's total energy consumption [16], or ~5 times China's total gasoline demand in 2008.

4.2. Spatial pattern of waste N and potential energy production

Waste N was mainly from regions with large populations and developed agriculture, such as Henan and Shandong provinces in the North China Plain, followed by Central China, and Northwestern China was the region with the lowest waste N (Fig. 3a). The distribution pattern of per capita waste N was the inverse of total waste N: Western China ranked first, followed by Central and Eastern China (Fig. 3b). Per capita waste N in Tibet was the largest, reaching 64 kg N year^{-1}, and the low population density and relatively developed livestock system might be the primary reason for that. The per capita waste N from the Eastern coastal region was less than 10 kg N year^{-1}: the high population density and high wastewater treatment ratio can explain that. On the basis of per hectare waste N distribution, there was a clear decreasing gradient from Southern to Northwestern China (Fig. 3c), which was consistent with the distribution of population density and N pollution [25]. The proportion of point source waste N to total waste N was higher in Eastern and Central China than in Western China (Fig. 3d), and the relatively high population density and developed industry, or under-developed agriculture could explain this pattern.

The total potential biofuel from BPWN is mainly from regions where waste N production and untilled land area are large (Fig. 3 and Table 3), e.g. Hebei, Heilongjiang and Sichuan provinces, and the total biofuel production from these three provinces accounted for 22% of total biofuel via BPWN in China. In Northwestern and Eastern China, where there is low waste N production or feasible land resources, the total biofuel production from these regions is lower than from the others (Table 2). However, on a per capita basis, the highest production is found in Tibet, 138.8 GJ year^{-1}, followed by Qinghai, Inner Mongolia and Heilongjiang. The common feature of these regions with high per capita biofuel production via BPWN is the low population density, meanwhile, cropland cultivation (e.g. Northeastern China) or livestock production (e.g. Western China) is developed.

The proportion of biofuel production via BPWN to total energy consumption is inversely related to per capita GDP (Fig. 4). The relatively high per capita biofuel production of BPWN and low per capita energy consumption mean that one-half of the local energy requirements could be supplied by BPWN in Western and Northeastern China (Table 2). This shows that these regions have the advantage and motivation to develop BPWN. In Tibet, in particular, the proportion of biofuel production via BPWN to total energy consumption is as high as ~140%; therefore,

Table 3
Untilled land resources, and land requirement for BPWN in China in 2008 (unit, 10^3 km^2 for land area).

Province	Untilled land [29]	Land requirement			S2/untilled (%)
		S1	S2	S3	
Beijing	2.2	3.0	3.9	2.2	177.2
Tianjin	0.7	3.1	3.8	0.7	548.5
Hebei	40.5	32.0	37.5	37.5	92.6
Shanxi	50.6	11.3	13.7	13.7	27.1
Inner Mongolia	150.6	14.2	16.0	16.0	10.6
Liaoning	15.1	17.5	20.9	15.1	138.1
Jilin	11.3	18.5	21.3	11.3	188.3
Heilongjiang	43.5	20.6	24.1	24.1	55.3
Shanghai	0.0	0.8	1.0	1.7	–
Jiangsu	1.5	7.4	8.8	2.6	584.0
Zhejiang	7.0	4.4	5.5	9.4	78.1
Anhui	7.5	8.7	10.4	12.8	138.9
Fujian	9.6	4.1	5.0	8.5	51.8
Jiangxi	11.3	5.2	6.5	11.1	57.5
Shandong	16.5	42.6	49.8	16.5	302.0
Henan	18.7	51.4	59.8	18.7	319.6
Hubei	21.2	8.5	10.1	17.3	47.6
Hunan	20.4	9.9	11.8	20.2	58.0
Guangdong	9.7	9.2	11.5	16.6	118.2
Guangxi	51.6	7.8	9.3	15.8	17.9
Hainan	2.6	1.5	1.7	2.9	65.3
Chongqing	15.2	4.1	5.1	8.8	33.7
Sichuan	57.7	12.0	14.5	24.8	25.1
Guizhou	27.0	7.4	8.7	14.8	32.1
Yunnan	73.0	8.2	9.3	15.9	12.8
Tibet	370.5	9.2	9.5	9.5	2.6
Shannxi	11.7	15.8	19.1	11.7	163.6
Gansu	161.1	10.1	12.3	12.3	7.6
Qinghai	248.4	4.4	4.9	4.9	2.0
Ningxia	8.2	2.6	3.0	3.0	36.8
Xinjiang	986.2	9.7	11.0	11.0	1.1
China	2451.1	365.0	429.6	391.3	17.5

S1–S3 indicate the waste N supply scenarios as defined in Table 2.

Tibet might be a clean fuel region with no need for fossil fuel consumption. It may provide a 'clean' example of the sustainable development of environmental pollution control and energy supply.

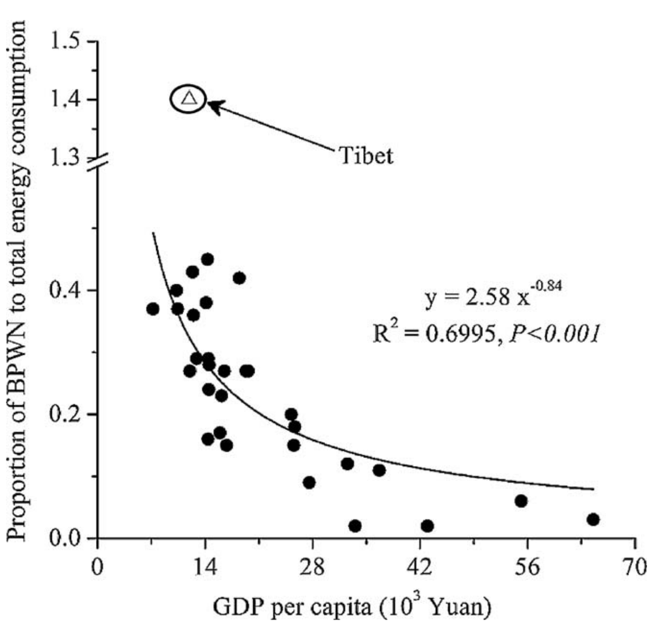

Fig. 4. Relationship between proportion of BPWN biofuel energy to total energy consumption and GDP per capita across China's 31 provinces in 2008. Tibet is an outlying data point with an extremely high proportion of BPWN biofuel energy to total energy consumption, and which is not included in the regression. 1 US dollar = 6.9 Yuan in 2008.

4.3. Feasibility analysis of BPWN in China

Abundant N and water supplies contribute to high biomass production [24]. Fortunately, water supply is coupled to waste N supply for BPWN. For instance, point source pollutants (waste N discharged from livestock factories and domestic and industrial wastewater) are always coupled to a large amount of water discharge that could be used for irrigation and reuse [17]. For nonpoint source pollution, such as N loss from cropland and natural ecosystems, waste N loss is caused by irrigation or precipitation [15]. Therefore, the N and water supply should not be the limiting factors for BPWN. The two plant species chosen in this study should fit the growth temperature requirements based on previous research in Europe, Australia and the United States [19]. Thus, the land requirement might be the only primary limiting factor for BPWN in China.

Table 3 shows the untilled land distribution in China, and the proportion of land used for BPWN to total untilled land. Although the land requirement for BPWN is only 17.5% of total untilled land on the country level for scenario S2, the feasible land resource in one-fifth of China's provinces is insufficient for BPWN (Fig. 5), for example, Tianjin, Shanghai, and Jiangsu province. This imbalance between land supply and requirement reduces the potential biofuel production by BPWN; meanwhile, it could lead to excess waste N lost to the environment and bring N pollution to these provinces. Insufficient land supplies reduce the energy supply potential by ~25%, from 21,595.9 to 16,436.3 PJ $year^{-1}$ in China. Therefore, future potential land supplies in these provinces could increase biofuel production in China, for example, urban parks can be used as CWs in domestic wastewater treatment in China [7] and Germany [17]. Meanwhile, the waste N transportation between nearby regions could also balance the waste N and land

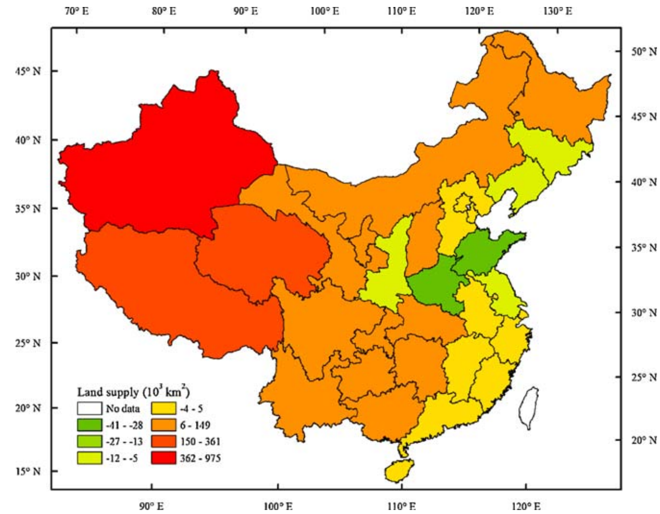

Fig. 5. Land supply ability for BPWN under the maximum waste N supply (scenario S2). Values in the legend indicate that the land supply is insufficient (negative number) or sufficient (positive number) for BPWN in each province. The magnitude of the values indicates how much the land supply is deficient or excessive.

resource supply although it might increase the transportation cost.

5. Uncertainty and risk analysis

5.1. Uncertainties

Although our estimates in this study are based on all available information, the accuracy is still limited by uncertainties due to data sources and assumptions [26]. Uncertainties that result from data derived from government publications, e.g. statistical yearbooks, fall within the range of approximately ±5% since they use an identical system for statistical analysis [16,26]. Furthermore, some variables used for N flux estimation in this study were taken from the existing literature, which may also introduce potential uncertainties (see Supplementary Data for details). Further research is required in these areas to give more detail about uncertainties so as to improve the accuracy of N flux estimation.

In this study, the net energy yield was assumed to be equal across the temperate zone and Qinghai–Tibet plateau, and tropical and subtropical zones in China. However, BPWN is affected by many factors, e.g. climate, engineering design, management, plant species selection, etc. (i) Climate difference. Since the water and nutrient supply are not the primary impacted factors for BPWN based on the above analysis, then solar radiation and annual temperature may introduce differences in the yield among different regions. (ii) Management difference. The routine maintenance and other management practices will significantly affect the biomass production [22] of BPWN. Differences in engineering control of the waste N retention time will have different effects on N loss and biomass production processes.

Our estimation was based on the assumption that the distribution patterns of waste N and feasible land are matched on a local scale. However, we may overestimate the potential energy production since the energy input for transportation would be increased if the feasible land is far from the waste N sources on a local scale, e.g. the shape of Inner Mongolia is narrow and long that across ~30 longitudes. In addition, although BPWN can use effluent water (or wastewater) for irrigation, there may still be a water deficiency pressure in dry regions, e.g. Northwestern China, since the evaporation loss is large there. Therefore, we may overestimate the potential of BPWN in dry regions.

5.2. Risks

BPWN may cause a series of negative environmental consequences. The N application rate to the BPWN has been estimated at 200–600 kg N ha^{-1} year^{-1}, even higher in regions with sufficient waste N supply, which would be much larger than that of current biofuel or agricultural production [2]. Low nitrogen use efficiency (NUE) has been found from cropland with a high N fertilization rate (about 300 kg N ha^{-1} year^{-1} [14]) giving massive N loss to the air or water [15], and resulting in air pollution, eutrophication, and nitrate accumulation in groundwater [27]. Therefore, the BPWN might bring secondary N pollution to the environment. However, the waste N would be discharged to the environment directly if there is no BPWN; in this case, the BPWN, in fact, contributes to the mitigation of environmental deterioration.

6. Conclusions

This paper discusses an alternative way of biofuel production via BPWN and at the same time reducing environmental N pollution. On the matter of NEB or NER, BPWN is more advantageous than the current biofuel production systems. Adopting China's 2008 data for the analysis, we found that BPWN can supply about 20% of its total energy consumption, equal to five times China's gasoline demand in that year. Per capita biofuel production from BPWN was higher in Western and Northeastern China, especially in Tibet, indicating that these regions have an advantage from BPWN. Further research on the relationship between land supply and waste N distribution on regional and local scales will help to refine the estimation of biofuel supply potential in China.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.rser.2011.07.062.

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